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Assessment of Efficiency and Sustainability in a Chemical Industry using Goal Programming and AHP

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Abstract

This paper proposes a methodology for continuous assessment and improvement of the efficiency and sustainability in a Chemical Industry. This segment was chosen due to its importance both in the international (sixth largest worldwide revenues) and in Brazilian economic scenario (fourth segment in importance in the formation of industrial GDP).

An exploratory analysis was performed by applying nonparametric techniques to measure and compare the efficiency and sustainability in a fictitious chemical production plant. The analyzed variables were identified and it was defined the importance (weight) of each of these by using the AHP (Analytic Hierarchy Process) method. It was defined a standard to be used as a benchmark and it was identified the implemented actions (projects) to achieve the proposed targets, using the technique of Goal Programming.

The variables were defined considering sustainability and efficiency performance indicators. For sustainability were used as reference the standards defined in "Responsible Care®" program and the efficiency performance indicators were chosen considering some key items used by the market to assess efficiency of a production plant.

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Keywords: Chemical Industry; Efficiency; Sustainability; AHP; Goal Programming.

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1. Introduction

The chemical industry provides raw materials and finished products for all productive sectors, playing an important role in the economy. Brazil is the sixth largest revenue with US $ 166 billion in 2011 [1] and the fourth segment in importance considering the formation of the industrial GDP, representing 9.9% of its total value [2]. The evolution of the net revenues started in 1995 with $ 41.4 billion and reached US $ 162.3 billion in 2013.

The chemical industry comprises the following segments with their respective revenues in 2013:

a) Chemical Products for Industrial use (US $ 72.2 billion);
b) Pharmaceuticals (US $ 26.5 billion);
c) Fertilizers (US $ 16.1 billion);
d) Toiletry, Perfumery and Cosmetics (US $ 14.7 billion);
e) Cleaning Products and the like (US $ 14.8 billion);
f) Agrochemicals (US $ 10.4 billion);
g) Paints, lacquers and varnishes (US $ 4.2 billion);
h) Artificial and synthetic (1.2 billion);
i) Other (US $ 2.2 billion).

Regarding the trade balance, there is a growth of imported products in the domestic market, starting with a rate of 7% in 1990 to 30% in 2013, representing a deficit of $ 32.2 billion in 2013 [3].

This scenario indicates a loss of competitiveness and according with the Council of Chemical Industry Competitiveness (*"Plano Brasil Maior",* an initiative of the Brazilian Federal Government, through the Ministry of Development, Industry and Trade, which focuses on innovation and productive consolidation of the industrial park Brazil, aiming at sustainable productivity gains) the following short-term measures are needed: increase competitiveness of raw material in terms of availability and prices; improved infrastructure; reduction in taxation; encouraging innovation and establishing more competitive interest rates.

Additionally it is crucial that companies reevaluate their production strategies [4], looking for increase efficiency in their production processes.

2. Objective

The objective of this paper is to study and propose a methodology, by applying a nonparametric technique, to measure and compare the efficiency and sustainability in a fictional chemical production plant [5].

In order to achieve this objective, it was identified the variables that will be analyzed as well as it was defined the importance (weight) of each of these variables using the Analytic Hierarchy Process - AHP [6]. It was also established a target; compared the obtained results with this one and identified the actions to be implemented in order to achieve the proposed targets by using the Goal Programming technique [7], [8].

The definition of the variables was made considering two types of performance indicators: a) sustainability indicators and b) efficiency indicators. For sustainability indicators was used as reference some of the standards defined in the program Responsible Care® (created by Canadian Chemical Producers Association) and for efficiency it was used some of the main indicators to track the performance of the company.

This study is useful for a company to measure their production efficiency and look for opportunities to improve its production process in order to maintain/increase its competitiveness and ensure its sustainability by maintaining their activities in the market.

As a result, employees are directly impacted by keeping their jobs and developing their professional careers. Indirectly the municipality, the state and the country are also affected by maintaining the jobs positions, assuring the tax revenue generated by the industrial activity and finally reducing the trade deficit for the chemical industry.

The study is limited to some fictional data of a production plant in the chemical industry, comparing them with a standard production (benchmarking).

3. Methodology

It was used an exploratory study based on modeling a hypothetical chemical industry, named as "Company X", is considered here. This company has the follow characteristics: continuous production (24 hours a day / 7 days a week / 365 days a year), with annual maintenance partial shutdown of 5 days for small cleaning and calibration and cyclic turnaround each two years for inspection, cleaning and new investment projects implementation.

To achieve the proposed objectives the study considers strategy opportunities to improve efficiency through Multi Criteria Decision Analysis using AHP and Goal Programming. As source of information it was used scientific papers, technical books, conference material, dissertations and Abiquim publications. Additionally, it was used the Responsible Care Program® as a reference to define the sustainability performance indicators.

For setting the values used in the model, it was considered the history of the last eight years and the targets were established considering values of "benchmarking" and the need of a continuous improvement process. The benchmarks were compared with the real values measured in the "Company X", based on an annual assessment (2013) and the action plan needed to minimize the identified gaps were translated into capital investments projects, implementation of new procedures or investment in training and awareness of the teams.

Figure 1 shows the model [9] with respective phases used to evaluate the process, considering AHP and Goal Programming methods.

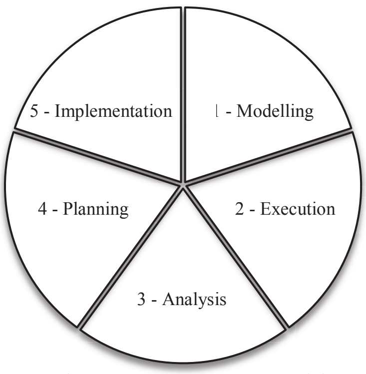

Fig. 1. Evaluation process steps for decision making

3.1 - Phase 1 (Modelling)

This stage defines the elements, the structure and procedures to compose the hierarchical model of the alternatives. Based on the Responsible Care Program® and on the Operational Excellence metric, it was used the performance indicators described in the table 1 to measure and compare the efficiency and sustainability in a production plant in the chemical industry:

Table 1 - Performance indicators model

GROUP	DEFINED VARIABLE	CODE	PERFORMANCE INDICATOR
Sustainability	Occupational Safety Indicators (IST)	IST1	Recordable accident frequency (own staff + contractors)
		IST2	Not recordable accident frequency (own staff)
		IST3	Severity of the accident (own staff + contractors)
	Process Safety Indicators (ISP)	ISP1	Events with fire or explosion, which caused loss over $ 25,000
		ISP2	Events with leaking of more than 2,300 kg of product
		ISP3	Process safety events that caused personal injuries with lost or death (own staff or contractors)s
	Environmental Indicators (IMA)	IMA1	Hazardous waste generation per amount of product produced (kg / ton product)
		IMA2	Waste classified as hazardous by NBR 10004/04 which are processed for final disposal (in%)
		IMA3	Waste classified as hazardous by NBR 10004/04 that are recycled, reused and / or reprocessed (in%)
		IMA4	Captured water and water purchased for industrial use (m3 / ton)
		IMA5	Water used in industrial processes per ton of product (m3 / ton)
		IMA6	Wastewater produced, treated and released into waterways (m3 / ton of product)
		IMA7	Wastewater produced and recycled after treatment (m3 / ton of product)
		IMA8	Total Carbon dioxide (CO2) emission (kg CO2 eq / ton of product):
		IMA9	Natural gas consumption as fuel per amount of products (kg / ton product)
		IMA10	Fuel oil and coal consumption per amount of products (kg / ton. Product)
		IMA11	Renewable fuel consumption per quantity of product (kg / ton product)
		IMA12	Total power consumption per amount of product (kwh / ton. Product)
Efficiency	Operational Excellence Indicators (IEO)	IEO1	OEE (Overall Effectiveness Equipment) (%)
		IEO2	OEC (Overall Effectiveness Capaticy) (%)
		IEO3	SCP (Specific Cost of Production) (US $ / kg)

3.2 - Phase 2 (Execution)

It was constructed matrices to compare the alternatives and criteria, as well as to calculate the consistency ratio of the matrices and to define the global priority vectors. In this step the alternatives are evaluated by binary combinations (pairs) for each criterion and the preferences are expressed by assigning a numerical value to each comparison using the Saaty scale. Based on the binary decisions made by the decision-maker, it was built a peer comparison matrix for each defined criterion or sub-criterion. It was used the software "MakeItRational" [10] to establish the relative importance of each performance indicator. Below in the figure 2, we can see the considered hierarchic model.

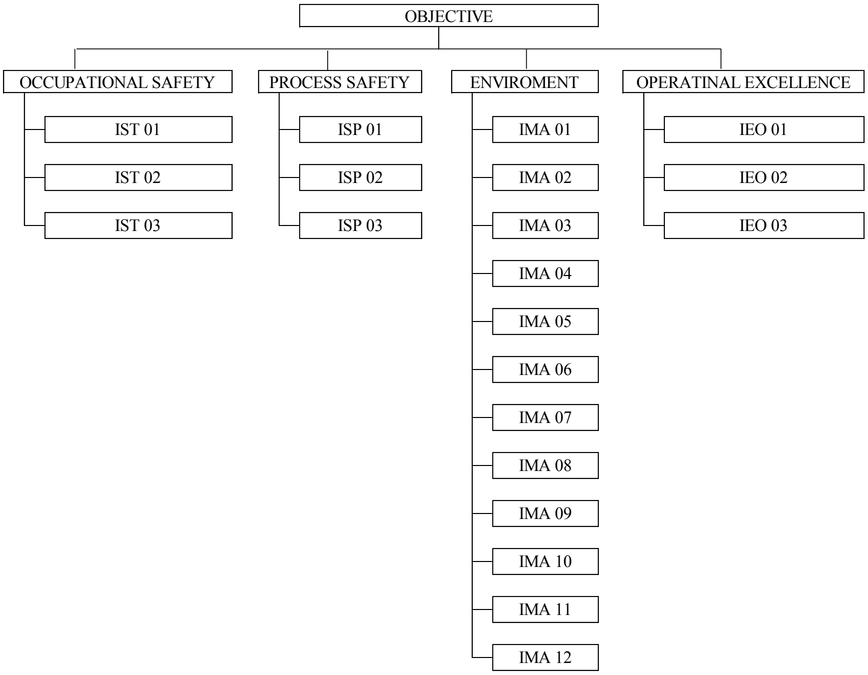

Fig. 2. Hierarchy model

3.3 - Phase 3 (Analysis)

In this phase the collected data and results (historical field information from “Company X”) are compared and analyzed, using the global priority vector and the performance of alternatives. It is also tested the consistency of the method and for that it was used the software "MakeItRational" for data analysis and definition of the relative importance of each of the performance indicators used.

The table 2 below lists, as result of the software “MakeItRational” application, the weight of each variable in relation to the corresponding performance indicator, as well as its overall weight.

Table 2 - Performance indicators - weight of each item

1st. Level Variable	1st. Level Variable Weight	2nd. Level Variable	Objective	2nd. Level Variable Weight	Global Weight	Goal	Results Company "X"	Diference % ResultsxGoals
Occupational Safety (IST)	23.22%	IST 01	Minimize	40%	9.3%	1.7	1.35	-21%
		IST 02	Minimize	20%	4.6%	4.9	5.05	3%
		IST 03	Minimize	40%	9.3%	46.6	29.6	-36%
Process Safety (ISP)	14.04%	ISP 01	Minimize	31.1%	4.4%	7.2	0	-100%
		ISP 02	Minimize	19.6%	2.7%	6.0	2.0	-67%
		ISP 03	Minimize	49.3%	6.9%	13.3	2.0	-85%
Enviroment (IMA)	23.22%	IMA 01	Minimize	8.3%	1.9%	2.2	2.3	5%
		IMA 02	Minimize	8.3%	1.9%	77.5	80.0	3%
		IMA 03	Minimize	8.3%	1.9%	19.3	16.6	-14%
		IMA 04	Minimize	8.3%	1.9%	4.6	5.4	16%
		IMA 05	Minimize	8.3%	1.9%	2.6	2.9	10%
		IMA 06	Minimize	8.3%	1.9%	1.1	1.5	36%
		IMA 07	Minimize	8.3%	1.9%	42.3	28.0	-34%
		IMA 08	Minimize	8.3%	1.9%	243.2	280.0	15%
		IMA 09	Minimize	8.3%	1.9%	32.0	39.0	22%
		IMA 10	Minimize	8.3%	1.9%	.2	0,0	-100%
		IMA 11	Minimize	8.3%	1.9%	5.7	2.1	-63%
		IMA 12	Minimize	8.3%	1.9%	316	380	20%
Operational Excellence (IEO)	39.52%	IEO 01	Maximize	40%	15.8%	88.7	75.0	15%
		IEO 02	Maximize	20%	7.9%	85.4	81.3	5%
		IEO 03	Maximize	40%	15.8%	4.0	5.1	27%

3.4 - Phase 4 (Planning)

Based on the results obtained in the phase 3, it was identified the variable that needs to be improved, considering the follow criteria:

a) The Global Weight of the variable must be equal or higher than 5% (defined as statistically representative) and the difference between the defined goal and the result measured in the "Company X" must be higher than 0 (zero).

b) The difference between the defined goal and the result measured in the "Company X" must be higher than 5% (defined as statistically representative) independent of the Global Weight of the variable.

Applying these criteria follow the result in the Table 3, highlighted in the column "Planning".

Table 3 – Identification in the column "Planning" of the item to be improved

1st. Level Variable	1st. Level Variable Weight	2nd. Level Variable	Objective	2nd. Level Variable Weight	Global Weight	Goal	Results Company "X"	Diference % ResultsxGoals	Planning
Occupational Safety (IST)	23.22%	IST 01	Minimize	40%	9.3%	1.7	1.35	-21%	Keep
		IST 02	Minimize	20%	4.6%	4.9	5.05	3%	Keep
		IST 03	Minimize	40%	9.3%	46.6	29.6	-36%	Keep
Process Safety (ISP)	14.04%	ISP 01	Minimize	31.1%	4.4%	7.2	0	-100%	Keep
		ISP 02	Minimize	19.6%	2.7%	6.0	2.0	-67%	Keep
		ISP 03	Minimize	49.3%	6.9%	13.3	2.0	-85%	Keep
Enviroment (IMA)	23.22%	IMA 01	Minimize	8.3%	1.9%	2.2	2.3	5%	Keep
		IMA 02	Minimize	8.3%	1.9%	77.5	80.0	3%	Keep
		IMA 03	Minimize	8.3%	1.9%	19.3	16.6	-14%	Keep
		IMA 04	Minimize	8.3%	1.9%	4.6	5.4	16%	Minimize
		IMA 05	Minimize	8.3%	1.9%	2.6	2.9	10%	Minimize
		IMA 06	Minimize	8.3%	1.9%	1.1	1.5	36%	Minimize
		IMA 07	Minimize	8.3%	1.9%	42.3	28.0	-34%	Keep
		IMA 08	Minimize	8.3%	1.9%	243.2	280.0	15%	Minimize
		IMA 09	Minimize	8.3%	1.9%	32.0	39.0	22%	Minimize
		IMA 10	Minimize	8.3%	1.9%	.2	0,0	-100%	Keep
		IMA 11	Minimize	8.3%	1.9%	5.7	2.1	-63%	Keep
		IMA 12	Minimize	8.3%	1.9%	316	380	20%	Minimize
Operational Excellence (IEO)	39.52%	IEO 01	Maximize	40%	15.8%	88.7	75.0	15%	Maximize
		IEO 02	Maximize	20%	7.9%	85.4	81.3	5%	Maximize
		IEO 03	Maximize	40%	15.8%	4.0	5.1	27%	Minimize

3.5 – Phase 5 (Implementation)

In this phase it was set targets using Goal Programming method to establish continuous improvement process. It was used the Lexicographic (or Pre-Emptive) Goal Programming technic, considering the follow mathematic model:

3.5.1 – Mathematic Model:

3.5.1.1 – Decision Variables

a - Binary Variables:

$P_n = 1$ if Project will be implemented;

$P_n = 0$ if Project will not be implemented;

b – Linear Variables:

FG_{kj} - how much is necessary to increase in order to achieve the deviation ‘k’ in the year ‘j’.

EG_{kj} - how much is necessary to reduce in order to achieve the deviation ‘k’ in the year ‘j’.

CT_{kj} – overall contribution of the implemented Projects to achieve the deviation ‘k’ in the year ‘j’

Considering that:

i : identification of all the proposed projects to reduce the deviation

k : identification of all the deviation that needs to be reduced

j : year considered for the Projects implementation

c – Constant:

MG_{kj} - target to reduce the deviation ‘k’ in the year ‘j’ (in the deviation unit)

PF_{kj} - measure of the importance in not reducing the deviation ‘k’in the year ‘j’

OP_{ij} - required budget to implement the Project ‘i’ in the year ‘j’, expressed in thousand Reais (T R$)

O_j - available budget in the year ‘j’, expressed in thousand Reais (T R$).

CPG_{ikj} – how much the Project ‘i’ contribute to reduce the deviation ‘k’ in the year ‘j’.

d - Objective Function: as the equation 1 shows bellow, used to minimize deviation.

$$Z = \text{minimize deviation or Min } Z = \left(\sum_k \sum_j \frac{FG_{kj} * PG_{kj}}{MG_{kj}}\right) \quad (1)$$

Considering that:

$\frac{FG_{kj} * PG_{kj}}{MG_{ki}}$ ⇨ determines the impact of each deviation in the total deviation of the year. Although we have an objective function (‘Z’), the key decision variable will be the definition of the project will be implemented or not (represented by PJ_{TI})

e – Deviation of each indicator per year: this restriction measure how much a contribution makes the value above or below the defined target, according the equation 2:

$$\left(\left(\textstyle\sum_y\right) CT_{ky}\right) + FG_{kj} - EG_{kj} = MG_{kj} \quad (2)$$

Considering that:

$+FG_{kj} - EG_{kj}$ = difference or exceeded value

y = index that represent the total amount of years, where $y \leq j$

If the target of any performance indicator is achieved, then $FG_{kj} = 0$.

Using this approach it is possible to determine how much time will be necessary to achieve a specific goal, considering the Investment budget restrictions.

3.5.2 – Target definition considering the weight of each performance indicator using AHP method.

Based on the obtained results it was defined the follow targets with respective weights, according demonstrated in the table 4:

1st. Level Variable	2nd. Level Variable		Objective	2nd. Level Variable Weight	Global Weight	Adjusted Global Weight	Results Company "X"	Goal	Planning
Enviroment (IMA)	IMA 04	Captured water and purchased water	Minimize	8.3%	1.9%	3.8%	5.4	4.60	Minimize
	IMA 05	Water used in industrial processes	Minimize	8.3%	1.9%	3.8%	2.9	2.60	Minimize
	IMA 06	Wastewater produced, treated and released into waterways	Minimize	8.3%	1.9%	3.8%	1.5	1.10	Minimize
	IMA 08	Total Carbon dioxide (CO2) emission	Minimize	8.3%	1.9%	3.8%	280	243	Minimize
	IMA 09	Natural gas consumption as fuel	Minimize	8.3%	1.9%	3.8%	39.0	32.0	Minimize
	IMA 12	Total power consumption	Minimize	8.3%	1.9%	3.8%	380	316	Minimize
Operational Excellence (IEO)	IEO 01	OEE (Overall Effectiveness Equipment)	Maximize	40.0%	15.8%	30.9%	75.0	88.7	Maximize
	IEO 02	OEC (Overall Effectiveness Capaticy)	Maximize	20.0%	7.9%	15.5%	81.3	85.4	Maximize
	IEO 03	Specific Cost of Production	Minimize	40.0%	15.8%	30.9%	5.1	4.0	Minimize
				TOTAL	51.1%	100.0%			

Table 4 – Adjusted calculation of the global weight of the considered performance indicators.

The initial global weight, showed in the table 3 was adjusted considering the performance indicators to be improved. A new calculation was performed and the result show that the variables IEO1 (weight = 30,9%), IEO3 (weight 30,9%) e IEO 2 (weight = 15,5%) have a highest impact in the global performance of the Company.

3.5.3 – List of Projects that can be implemented

The table 5 below shows the Projects that can be implemented and the respective impact in the defined performance index:

Table 5 – Identified projects (P1-P10) with respective impact in the performance indicators (estimated values in thousand R$ = TR$)

PERFORMANCE IDENTIFICATOR	EXPECTED RESULTS	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
IMA 04	4.60	0	0	0	TR$ 2,000	0	0	0	0	0	TR$ 6,000
IMA 05	2.60	0	0	0	TR$ 1,000	0	0	0	0	0	0
IMA 06	1.10	0	0	TR$ 1,000	0	0	0	0	0	0	TR$ 1,000
IMA 08	243	0	0	0	0	TR$ 1,500	0	0	0	0	0
IMA 09	32.0	TR$ 2,000	0	0	0	0	0	0	0	0	0
IMA 12	316	0	TR$ 1,000	0	0	0	0	0	0	TR$ 1,000	0
IEO 01	88.7	0	0	0	0	0	TR$ 4,000	TR$ 1,000	TR$ 1,000	0	0
IEO 02	85.4	0	0	0	0	0	0	TR$ 3,000	0	TR$ 1,000	0
IEO 03	4.0	0	0	0	0	0	0	0	TR$ 3,000	0	0

3.5.4 – Restriction: the investment budget of the ‘Company X’ cannot be higher than TR$ 12.000

3.5.5 – Formulation: the table 6 presents an application model of Lexicographic Goal Programming, processed using the supplement Solver of the program Microsoft Excel [11].

Table 6 – Lexicographic Goal Programming Model – values in TR$

PERFORMANCE INDICATOR	PROJECTS																				DEVIATION				GOAL	WEIGHT	
IMA 04	0P1	+	0P2	+	0P3	+	2,000P4	+	0P5	+	0P6	+	0P7	+	0P8	+	0P9	+	6,000P10	+	n1	-	p1	=	4.6	0.038	
IMA 05	0P1	+	0P2	+	0P3	+	1,000P4	+	0P5	+	0P6	+	0P7	+	0P8	+	0P9	+	0P10	+	n2	-	p2	=	2.6	0.038	
IMA 06	0P1	+	0P2	+	1,000P3	+	0P4	+	0P5	+	0P6	+	0P7	+	0P8	+	0P9	+	1,000P10	+	n3	-	p3	=	1.1	0.038	
IMA 08	0P1	+	0P2	+	0P3	+	0P4	+	1,500P5	+	0P6	+	0P7	+	0P8	+	0P9	+	0P10	+	n4	-	p4	=	243	0.038	
IMA 09	2,000P1	+	0P2	+	0P3	+	0P4	+	0P5	+	0P6	+	0P7	+	0P8	+	0P9	+	0P10	+	n5	-	p5	=	32.0	0.038	
IMA 12	0P1	+	1,000P2	+	0P3	+	0P4	+	0P5	+	0P6	+	0P7	+	0P8	+	1,000P9	+	0P10	+	n6	-	p6	=	316	0.038	
IEO 01	0P1	+	0P2	+	0P3	+	0P4	+	0P5	+	4,000P6	+	0P7	+	0P8	+	0P9	+	0P10	+	n7	-	p7	=	88.7	0.309	Prio1
IEO 02	0P1	+	0P2	+	0P3	+	0P4	+	0P5	+	0P6	+	3,000P7	+	0P8	+	1,000P9	+	0P10	+	n8	-	p8	=	85.4	0.155	Prio3
IEO 03	0P1	+	0P2	+	0P3	+	0P4	+	0P5	+	0P6	+	0P7	+	3,000P8	+	0P9	+	0P10	+	n9	-	p9	=	4,0	0.309	Prio2
Restriction	P1	+	P2	+	P3	+	P4	+	P5	+	P6	+	P7	+	P8	+	P9	+	P10	=	12,000						

Considering the prioritization of the performance indicators IEO 01, IEO 02 and IEO 03, and the investment budget restriction, the follow Projects will be prioritized as result of the Goal Programming analysis:

- Project P06 = R$ 4 million with impact in the performance indicator IEO 01;
- Project P07 = R$ 3 million with impact in the performance indicator IEO 02;
- Project P08 = R$ 3 million with impact in the performance indicator IEO 03;
- Project P09 = R$ 2 million with impact in the performance indicators IEO 02 and IMA 12;
- Total Investment = R$ 12 million (respecting the defined investment budget).

4. Conclusions and recommendation for further analysis

Considering the importance of the chemical industry for both global and Brazilian economy, this study proposes a methodology for continuous evaluation aiming to improve efficiency and sustainability and to meet this expectation it was performed an exploratory analysis using nonparametric techniques.

The follow topics are the basis to formulate and perform this study:

- How can we measure the efficiency and sustainability of a Company (variable definition)
- What are the importance (weight) of each of the defined variables
- Which action plan will be established to achieve the defined targets

It was used a model to apply AHP and Goal Programming technique in order to select the best alternative, considering the following process steps:

- Modeling - define the elements and procedures to compose the alternatives hierarchical model
- Execution - construction of a matrix to compare alternatives and criteria
- Analysis of the collected data and the results of the aggregation and classification procedures
- Planning: identification of the variables that need to be prioritized to improve the results
- Implementation: define the targets and the action plan to meet these targets

To define the variables that represent sustainability it was used as reference some of the Responsible Care® performance indicators, based on the data collected in the period 2006-2013. The target was established considering an improvement of 10% for the best value in this period.

To define the variables that represent efficiency it was used as reference some technical and economic performance indicators in order to prioritize the improvement of availability, reliability and manufacturing cost.

The base was the performance history of fictitious company ('Company X') from 2006 to 2013, considering an improvement of 10% for the best value in this period.

The importance (weight) of each of the considered variables was defined using AHP methodology, which also enabled the comparison of "real x target" values and to perform the analysis it was used the software "MakeItRational".

The definition of an action plan to select and implement the investment projects that will enable to minimize the gaps between "real x target" values was performed by using the Lexicographic Goal Programming method.

The final result shows that due to the limitation of the capital investment budget (defined as R$ 12 million) it needs to be selected the projects that increase the performance of the variables with higher weight of the selected set defined for this analysis. As result of this approach, the projects that increase the results of the variables IEO 01, IEO 02 and IEO 03 were selected. As side effect, one of these projects also improves the result of the performance indicator IMA 12.

Finally, the objective of this study was completely achieved, making it possible for the management of 'Company X' to identify in a clear and systematic way the potential improvements to increase sustainability and efficiency in the production. This study needs to be considered as part of a continuous improvement process by applying the PDCA cycle [12] as the achievement of the defined goals will not be reached only in one year.

As a recommendation for future studies, this analysis can be applied not only in any Chemical or Petrochemical Industry (continuous or batch processes) but also in other Companies with a defined production process, considering only the need to select the appropriate variables that are suitable with activity that will be analyzed.

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